REC'D 26 MAY 2005
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EP/05/51243

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Patentanmeldung Nr. | Patent application No. | Demande de brevet n°

04101634.6

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Le Président de l'Office européen des brevets
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R C van Dijk

Anmeldung Nr:
Application no.: 04101634.6
Demande no:

Anmeldetag:
Date of filing: 20.04.04
Date de dépôt:

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Bezeichnung der Erfindung/Title of the invention/Titre de l'invention:
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Optical data storage system and method of optical recording and/or reading

In Anspruch genommene Prioriät(en) / Priority(ies) claimed /Priorité(s) revendiquée(s)
Staat/Tag/Aktenzeichen/State/Date/File no./Pays/Date/Numéro de dépôt:

Internationale Patentklassifikation/International Patent Classification/
Classification internationale des brevets:

G11B7/00

Am Anmeldetag benannte Vertragstaaten/Contracting states designated at date of filing/Etats contractants désignées lors du dépôt:

AT BE BG CH CY CZ DE DK EE ES FI FR GB GR HU IE IT LU MC NL
PL PT RO SE SI SK TR LI

Optical data storage system and method of optical recording and/or reading

The invention relates to an optical data storage system for recording and/or reading, using a radiation beam, having a wavelength λ, focused onto a data storage layer of an optical data storage medium, said system comprising:

- the medium having a cover layer that is transparent to the focused radiation beam,
- an optical head, including an objective having a numerical aperture NA, said objective including a solid immersion lens that is adapted for being present at a free working distance of smaller than $\lambda/10$ from an outermost surface of said medium and arranged on the cover layer side of said optical data storage medium, and from which solid immersion lens the focused radiation beam is coupled by evanescent wave coupling into the cover layer of the optical data storage medium during recording/reading.

The invention further relates to a method of optical recording and/or reading with such a system.

A typical measure for the focussed spot size or optical resolution in optical recording systems is given by $r = \lambda/(2NA)$, where λ is the wavelength in air and the numerical aperture of the lens is defined as $NA = \sin\theta$, see **Fig. 1**. In **Fig. 1a**, a so-called air-incident configuration is drawn in which the data storage layer is at the surface of the data storage medium (so-called <u>first-surface data storage</u>). In **Fig. 1b**, a cover layer with refractive index n protects the data storage layer from a.o. scratches and dust.

From these figures it is inferred that the optical resolution is unchanged if a cover layer is applied on top of the data storage layer: On the one hand, in the cover layer, the internal opening angle θ' is smaller and hence the internal numerical aperture NA' is reduced, but also the wavelength in the medium λ' is shorter by the same factor n_0. It is desirable to have a high optical resolution because the higher the optical resolution, the more data can be stored on the same area of the medium. Straight forward methods of increasing the optical resolution involve widening of the focused beam opening angle at the cost of lens complexity, narrowing of allowable disk tilt margins, etc. or reduction of the in-air wavelength i.e. changing the colour of the scanning laser.

Another proposed method of reducing the focussed spot size in an optical disk system involves the use of a solid immersion lens (SIL), see **Fig. 2**. In its simplest form, the SIL is a half sphere centred on the data storage layer, see **Fig. 2a**, so that the focussed spot is on the interface between SIL and data layer. In combination with a cover layer of the same refractive index, $n_0' = n_{SIL}$, the SIL is a tangentially cut section of a sphere which is placed on the cover layer with its (virtual) centre again placed on the storage layer, see **Fig. 2b**. The principle of operation of the SIL is that it reduces the wavelength at the storage layer by a factor n_{SIL}, the refractive index of the SIL, without changing the opening angle θ. The reason is that refraction of light at the SIL is absent since all light enters at right angles to the SIL's surface (compare **Fig. 1b** and **Fig. 2a**).

Very important, but not mentioned up until this point, is that there is a very thin air gap between SIL and recording medium. This is to allow for free rotation of the recording disk with respect to the recorder objective (lens plus SIL). This air gap should be much smaller than an optical wavelength (typically it should be smaller than λ/10) such that so-called evanescent coupling of the light in the SIL to the disc is still possible. The range over which this happens is called the near-field regime. Out side this regime, at larger air gaps, total internal reflection will trap the light inside the SIL and sent it back up to the laser. Note that in case of the configuration with cover layer as depicted in **Fig. 2b**, that for proper coupling the refractive index of the cover layer should be at least equal to the refractive index of the SIL, see **Fig. 3** for further details.

Waves below the critical angle propagate through the air gap without decay, whereas those above the critical angle become evanescent in the air gap and show exponential decay with the gap width (see **Fig. 3**). At the critical angle $NA = 1$. For large gap width all light above the critical angle reflects from the proximate surface of the SIL by total internal reflection (TIR).

For a wavelength of 405 nm, as is the standard for Blu-ray optical Disc (BD), the maximum air-gap is approximately 40 nm, which is a very small free working distance (FWD) as compared to conventional optical recording. The near-field air gap between data layer and the solid immersion lens (SIL) should be kept constant within 5 nm or less in order to get sufficiently stable evanescent coupling. In hard disk recording, a slider-based solution relying on a passive air bearing is used to maintain this small air gap. In optical recording, where the recording medium must be removable from the drive, the contamination level of the disk is larger and will require an active, actuator-based solution to control the air gap. To this end, a gap error signal (GES) must be extracted, preferably from the optical data signal

already reflected by the optical medium. Such a signal can be found, and a typical gap error signal is given in **Fig. 4**. Note that it is common practice in case a near-field SIL is used to define the numerical aperture as $NA = n_{SIL} \sin\theta$, which can be larger than 1.

In **Fig. 4** shows a measurement (taken from **Ref. [1]**) of the amounts of reflected light for both the parallel and perpendicular polarisation states with respect to the linearly polarised collimated input beam from a flat and transparent optical surface ("disc") with a refractive index of 1.48. These measurements are in good agreement with theory. The evanescent coupling becomes perceptible below 200 nm (the light vanishes in to the "disc") and the total reflection drops almost linearly to a minimum at contact. This linear signal may be used as an error signal for a closed loop servo system of the air gap. The oscillations in the horizontal polarisation are caused by the reduction of the number of fringes within $NA = 1$ with decreasing gap thickness.

More details about a typical near-field optical disc system can be found in **Ref. [2]**.

A root problem for optical recorder objectives, either slider-based or actuator-based, having a small working distance (typically less than 50 μm), is contamination of the optical surface closest to the storage medium occurs. This is due to re-condensation_of water, which may be desorbed from the storage medium because of the high surface temperature (typically 250 °C for MO recording and 650 °C for PC recording) resulting from the high laser power and temperature required for writing data in (or even reading data from) the data recording layer. The contamination ultimately results in malfunctioning of the optical data storage system due to runaway of, for example, the servo control signals of the focus and tracking system. This problem is a.o. described in the IDs, filings and patents given in **Refs. [3]-[5]**.

The problem becomes more severe for the following cases: high humidity, high laser power, low optical reflectivity of the storage medium, low thermal conductivity of the storage medium, small working distance and high surface temperature.

A known solution to the problem is to shield the proximal optical surface of the recorder objective from the data layer by a thermally insulating cover layer on the storage medium. An invention based on this insight is for example given in **Ref. [4]**.

Obviously, putting a cover layer on the near-field optical storage medium has the additional advantage that dirt and scratches can no longer directly influence the data layer.

However, by putting a cover layer onto a near-field optical system, new problems arise, which lead to new measures to be taken.

Normally, the accuracy by which the near-field air gap between data layer and the solid immersion lens (SIL) should be kept constant within 5 nm or less in order to get sufficiently stable evanescent coupling. In case a cover layer is used, the air gap is between cover layer and SIL, see **Fig. 2b**. Again, the air gap should be kept constant to within 5 nm. Clearly, the SIL focal length should have an offset to compensate for the cover layer thickness, such as to guarantee that the data layer is in focus at all times. Note that the refractive index of the cover layer, if it is lower than the refractive index of the SIL, determines the maximum possible numerical aperture of the system.

In order to obtain sufficient thermal isolation, the dielectric cover layer thickness should be more than approximately 0.5 μm, but preferably is of the order of 2-10 μm. Taken together this means that by controlling the width of the air gap only, the thickness variation of the cover layer Δh should be (much) smaller than the focal depth $\Delta f = \lambda/(2NA^2)$ in order to guarantee that the data layer is in focus: $\Delta h < \Delta f$, see **Fig. 5**. If we take the wavelength $\lambda = 405$ nm and numerical aperture $NA = 1.45$ we find that $\Delta f \approx 50$ nm. For spin-coated layers of several microns thickness this means less than a percent of thickness variation over the entire data area of the disc, which seems a challenging accuracy.

It is an object of the invention to provide an optical data storage system for recording and/or reading of the type mentioned in the opening paragraph, in which reliable data recording and read out is achieved using a near-field solid immersion lens in combination with a cover layer. It is an further object to provide a method of optical recording and/or reading for such a system.

This object has been achieved in accordance with the invention by an optical data storage system, which is characterized in that the optical head comprises:

- a first adjustable optical element corresponding to the solid immersion lens,
- means for axially moving the first optical element and dynamically keeping constant the distance between cover layer and solid immersion lens,
- a second adjustable optical element,
- means for dynamically adjusting the second optical element for changing the focal length of the objective.

Given that the cover layer does not have sufficiently small thickness variation Δh, say its thickness varies by more than 50-100 nm, we propose a dynamic correction of focal length to compensate for cover layer thickness variations, in addition to the dynamic air gap correction.

The purpose is that the data layer is in focus and at the same time the air gap between SIL and cover layer is kept constant so that proper evanescent coupling is guaranteed. Keeping constant means not more variation in air gap than 5 nm, preferably 2 nm.

The optical objective should contain at least two adjustable optical elements.

For example, an objective lens comprising two elements which can be axially displaced to adjust the focal length of the pair without substantially changing the air gap. The air gap can then be adjusted by moving the objective as a whole, see **Fig. 6**. In general, a certain amount of spherical aberration will remain. In some cases, optimum design of the lens system and cover layer combination will meet the system requirements, in other cases active adjustment of spherical aberration will be required and further measures will have to be taken.

In an embodiment the second optical element is present in the objective.

In another embodiment the second optical element is present outside the objective.

The second optical element may e.g. be axially movable with respect to the first optical element. Alternatively the second optical element has a focal length which is electrically adjustable, e.g. by electrowetting or electrically influencing the orientation of liquid crystal material.

The further object has been achieved in accordance with the invention by a method of optical recording and reading with a system as described above, wherein:

- the free working distance is kept constant by using a first, relatively high bandwidth servo loop based on a gap error signal, e.g. derived from the amount of evanescent coupling between the solid immersion lens and the cover layer,
- the first optical element is actuated based on the first servo loop,
- a second, relatively high bandwidth servo loop is active based on a focus control,
- the second optical element is adjusted based based on the second servo loop in order to retrieve an optimal modulated signal. By relatively high bandwidth is meant a normal optical recording focus servo bandwidth, e.g. several kHz.

In an embodiment the focus control signal is derived from the modulation depth of a modulated signal recorded in the data storage layer.

In an embodiment the modulated signal is present as pre-recorded data in the optical data storage medium, e.g. in a lead-in area of the optical data storage medium.

In another embodiment the modulated signal is present as a wobbled track of the optical data storage medium.

When the focus servo is derived from the modulation depth of a modulated signal recorded in the data storage layer a small continuous oscillation of the focal depth, i.e. a periodic modulation super imposed on the focus adjustment signal, is needed. Small means of the order of a focal depth. This is in order to determine in which direction the servo should be adjusted for finding the maximum modulation depth.

In another embodiment the focus control signal is derived from an S-curve type focus error signal.

Two coupled servo loops are required:

- One for the air gap, which makes the proximate surface of the optical objective follow the surface of the cover layer.
- One for the focal length, which keeps the data layer within the focal depth by varying the focal length of the optical objective.

Note that the servo loops are dependent on each other. The servo bandwidths and the coupling constant are parameters to be determined for a practical solution.

A possible block diagram of the double servo system is shown in **Fig. 7.**

A gap actuator (GA) is used for control of the air gap. This gap actuator is fitted with a smaller focus actuator (FA) that is used to control the focal position. Note that this smaller focus actuator may have a much smaller bandwidth than the larger gap actuator because it only needs to suppress cover layer thickness variations that are of the order of several microns. Furthermore the residual position error of the first lens is quite large because of the added magnification from the SIL that is kept at a constant distance to the disc. Thus a relatively large position error for the first lens results in a much smaller error in the focal position on the disc.

The focus actuator is driven by a PID controller (PID 1) with a conventional normalised (astigmatic or Foucault) focus error signal (FEN) as input. The normalised focus error signal is generated by divider 1 from a difference signal (ΔFES) and sum signal (ΣFES) from a set of photodiodes. A focus offset signal and focus pull-in procedure is fed into the controller by a central microprocessor (μProc). The gap actuator is driven by a second PID

controller (PID 2), using a normalised gap error signal (GEN) as input. This normalised gap error signal is generated by a divider that divides the gap error signal (GES) by the focus sum signal (or a signal from a forward sense diode). A controller set point and air gap pull-in procedure is fed into the controller by the central microprocessor.

Two control signals are required:

- The width of the air gap can be controlled using an error signal derived from the amount of evanescent coupling between SIL and cover layer. In **Fig. 4** a typical gap error signal (GES) is shown
- The focal length can be controlled using a conventional S-curve focus error signal (FES), see **Fig. 8**.

Typical example or possible embodiments

In the DVR project a dual lens actuator has been designed, see **Refs. [6]** which has a Lorentz motor to adjust the distance between the two lenses within the recorder objective. The lens assembly as a whole fits within the CDM12 actuator. The dual lens actuator consists of two coils that are wound in opposite directions, and two radially magnetised magnets. The coils are wound around the objective lens holder and this holder is suspended in two leaf springs. A current through the coils in combination with the stray field of the two magnets will result in a vertical force that will move the first objective lens towards or away from the SIL. A near field design may look like the drawing in **Fig. 9**.

A first embodiments of an optical objective with variable focal position is shown in **Figs. 6** and **9**, and it is repeated in **Fig. 10**. Alternative embodiments to change the focal position of the system comprise, for example, adjustment of the laser collimator lens, see **Fig. 11**, or a switchable optical element based on electrowetting or liquid crystal material, see **Figs. 12** and **13** and also **Ref. [7]**. These measures, of course, can be taken simultaneously.

Figure 1: Normal far-field optical recording objective and data storage disk. a) Without cover layer, and b) with cover layer.

Figure 2: Near-Field optical recording objective and data storage disk. a) Without cover layer. The effective wavelength is reduced to $\lambda' = \lambda/n_{SIL}$. b) with cover layer, $\lambda' = \lambda/n_0'$. The width of the air gap is typically 25-40 nm (but at least less than 100 nm), and is not drawn to scale. The thickness of the cover layer typically is several microns but is also not drawn to scale.

Figure 3: Total internal reflection occurs for NA>1 if the air gap is too wide. If the air gap is thin enough, the evanescent waves make it to the other side and in the transparent disk become propagating again. Note that if the refractive index of the transparent disk is smaller than the numerical aperture, n_0'<NA, that some waves remain evanescent and that effectively NA=n_0'.

Figure 4: Measurement of the total amount of the reflected light for the polarisation states parallel and perpendicular to the polarisation state of the irradiating beam, and the sum of both. The perpendicular polarisation state is suitable as an air-gap error signal for the near-field optical recording system.

Figure 5: Thickness variation of the cover layer may be larger than the focal depth.

Figure 6: Example of an embodiment and the principle of operation of a dual actuator in case of varying cover layer thickness. a) The storage layer is in focus and the air gap is kept constant. b) The cover layer thickness varies, but still the air gap is kept constant by moving both lenses simultaneously. c) The first lens is displaced to regain focus on the storage layer.

Figure 7: Block diagram of the double servo required to drive the dual lens actuator.

Figure 8: Example of a conventional S-curve type focus error signal (FES). In case of near-field optical recording such a signal can be obtained from the optical signal if the cover layer thickness is much larger than the focal depth, h >> Δf.

Figure 9: A cross section of a possible embodiment of a dual lens actuator for near field. It is based on the HNA design for DVR, see Ref. [6].

Figure 10: Defocus can be obtained by moving the first lens with respect to the SIL using the Focus Control (FC). The air gap is kept constant using the Gap Control (GC).

Figure 11: Defocus also can be obtained by moving the laser collimator lens with respect to the objective.

Figure 12: A switchable optical element based on electrowetting (EW) or liquid crystal (LC) material can be used to adjust the focal length of the optical system. It is also possible to simultaneously compensate for a certain amount of spherical aberration in this way.

Figure 13: A switchable optical element based on electrowetting or liquid crystal material can be used to adjust the focal length of the optical system. Here it is placed between the first lens and the SIL. It is also possible to simultaneously compensate for a certain amount of spherical aberration in this way.

References:

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[2] Kimihiro Saito, Tsutomu Ishimoto, Takao Kondo, Ariyoshi Nakaoki, Shin Masuhara, Motohiro Furuki and Masanobu Yamamoto, "Readout Method for Read Only Memory Signal and Air Gap Control Signal in a Near Field Optical Disc System", Jpn. J. Appl. Phys. 41, pp.1898–1902 (2002).

[3] Martin van der Mark and Gavin Phillips, "(Squeaky clean) Hydrophobic disk and objective", (2002); see international patent application publication WO 2004/008444-A2 (PHNL0200666, ID 610776) (priority 10 July 2002).

[4] Bob van Someren; Ferry Zijp; Hans van Kesteren and Martin van der Mark, "Hard coat protective thin cover layer stack media and system", see international patent application publication 2004/008441-A2 (2002) (PHNL0200667, ID 610932) (priority 10 July 2002).

[5] TeraStor Corporation, San Jose, California, USA, "Head including a heating element for reducing signal distortion in data storage systems", US 6.069.853 (Januari 8, 1999).

[6] Y.V. Martynov, B.H.W. Hendriks, F. Zijp, J. Aarts, J.-P. Baartman, G. van Rosmalen J.J.H.B. Schleipen and H.van Houten, "High numerical aperture optical recording: Active tilt correction or thin cover layer?", Jpn. J. Appl. Phys. Vol. 38 (1999) pp. 1786-1792.

[7] B.J. Feenstra, S. Kuiper, S. Stallinga, B.H.W. Hendriks, R.M. Snoeren, "Variable focus lens", see international patent application publication WO 2003/069380-A1. S. Stallinga, "Optical scanning device with a selective optical diaphragm", patent US 6707779 B1.

CLAIMS:

1. An optical data storage system for recording and/or reading, using a radiation beam, having a wavelength λ, focused onto a data storage layer of an optical data storage medium, said system comprising:
- the medium having a cover layer that is transparent to the focused radiation beam,
- an optical head, including an objective having a numerical aperture NA, said objective including a solid immersion lens that is adapted for being present at a free working distance of smaller than λ/10 from an outermost surface of said medium and arranged on the cover layer side of said optical data storage medium, and from which solid immersion lens the focused radiation beam is coupled by evanescent wave coupling into the cover layer of the optical data storage medium during recording/reading,

characterized in that,

the optical head comprises:
- a first adjustable optical element corresponding to the solid immersion lens,
- means for axially moving the first optical element and dynamically keeping constant the distance between cover layer and solid immersion lens,
- a second adjustable optical element,
- means for dynamically adjusting the second optical element for changing the focal length of the objective.

2. An optical recording and reading system as claimed in claim 1, wherein the second optical element is present in the objective.

3. An optical recording and reading system as claimed in claim 1, wherein the second optical element is present outside the objective.

4. An optical recording and reading system as claimed in claims 2 or 3 , wherein the second optical element is axially movable with respect to the first optical element.

5. An optical recording and reading system as claimed in any one of claims 2 or 3, wherein the second optical element has a focal length which is electrically adjustable, e.g. by electrowetting or by electrically influencing the orientation of liquid crystal material.

6. A method of optical recording and/or reading with a system as claimed in claim 1, wherein:

- the free working distance is kept constant by using a first, relatively high bandwidth servo loop based on a gap error signal, e.g. derived from the amount of evanescent coupling between the solid immersion lens and the cover layer,
- the first optical element is actuated based on the first servo loop,
- a second, relatively high bandwidth servo loop is active based on a focus control signal,
- the second optical element is adjusted based on the second servo loop in order to retrieve an optimal modulated signal.

7. A method as claimed in claim 6, wherein the focus control signal is derived from the modulation depth of a modulated signal recorded in the data storage layer.

8. A method as claimed in claim 6, wherein the focus control signal is derived from an S-curve type focus error signal.

9. A method as claimed in claim 7, wherein the modulated signal is present as pre-recorded data in the optical data storage medium.

10. A method as claimed in claim 7, wherein the modulated signal is present in a lead-in area of the optical data storage medium.

11. A method as claimed in claim 7, wherein the modulated signal is present as a wobbled track of the optical data storage medium.

ABSTRACT:

A transparent cover layer on a near-field optical recording medium is desirable a.o. for thermal insulation and mechanical protection. Due to cover layer thickness variation, both the gap width and focal distance will have to be controlled. Also, a varying amount of spherical aberration may have to be compensated for. A servo-controlled system is described in which at least two distinct error signals determine the position or optical properties of at least two elements in the objective.

Fig. 10

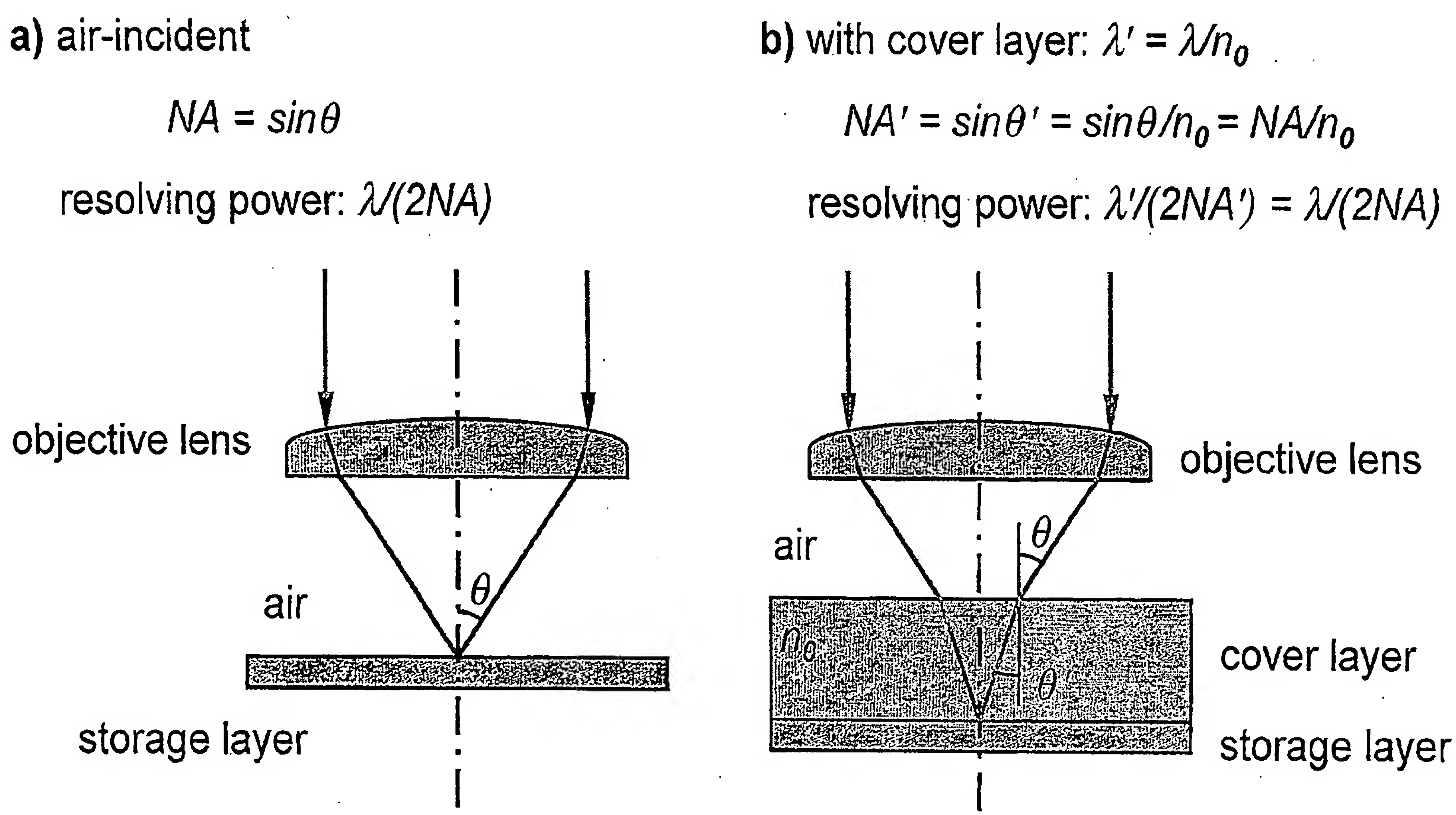
a) air-incident
$NA = sin\theta$
resolving power: $\lambda/(2NA)$
objective lens
air
θ
storage layer
b) with cover layer: $\lambda' = \lambda/n_0$
$NA' = sin\theta' = sin\theta/n_0 = NA/n_0$
resolving power: $\lambda'/(2NA') = \lambda/(2NA)$
objective lens
air
θ
n_0
θ'
cover layer
storage layer

Fig. 1

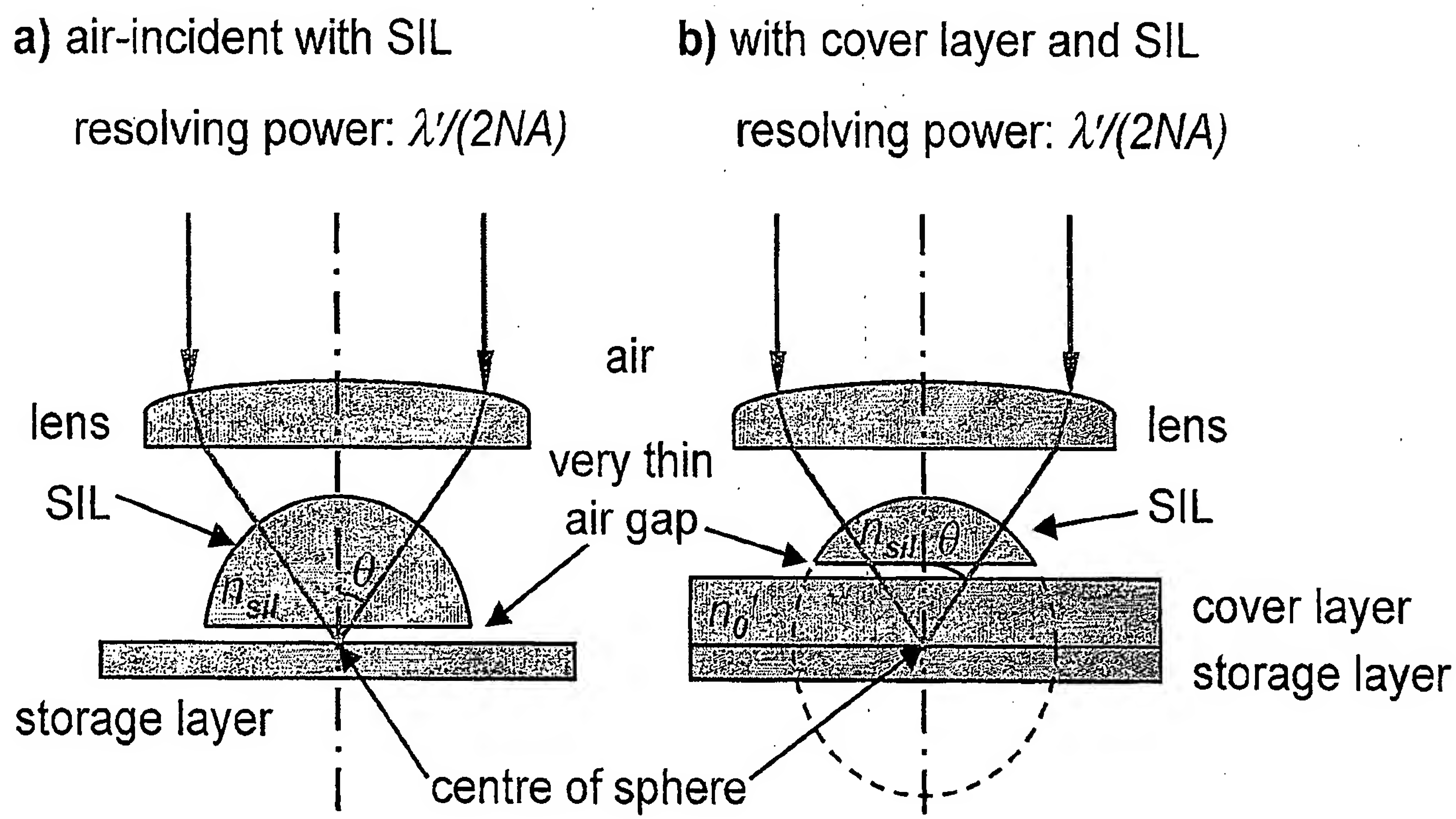
a) air-incident with SIL
resolving power: λ'/(2NA)
b) with cover layer and SIL
resolving power: λ'/(2NA)
air
lens
SIL
very thin
air gap
n_{SIL}
θ
n_0
lens
SIL
cover layer
storage layer
storage layer
centre of sphere

Fig. 2

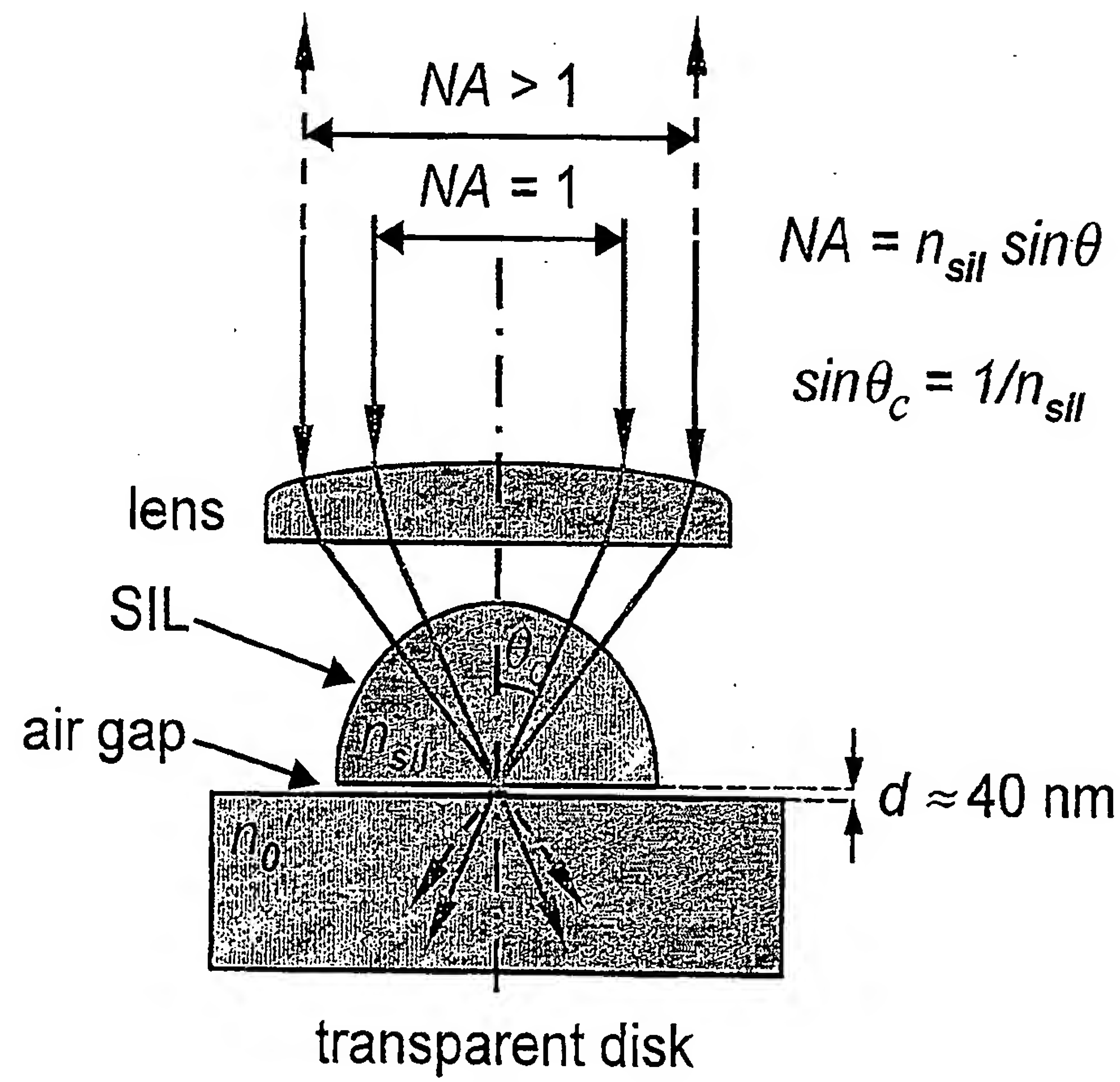
NA > 1
NA = 1
NA = n_sil sinθ
sinθ_c = 1/n_sil
lens
SIL
air gap
d ≈ 40 nm
θ_c
n_sil
n_0
transparent disk

Fig. 3

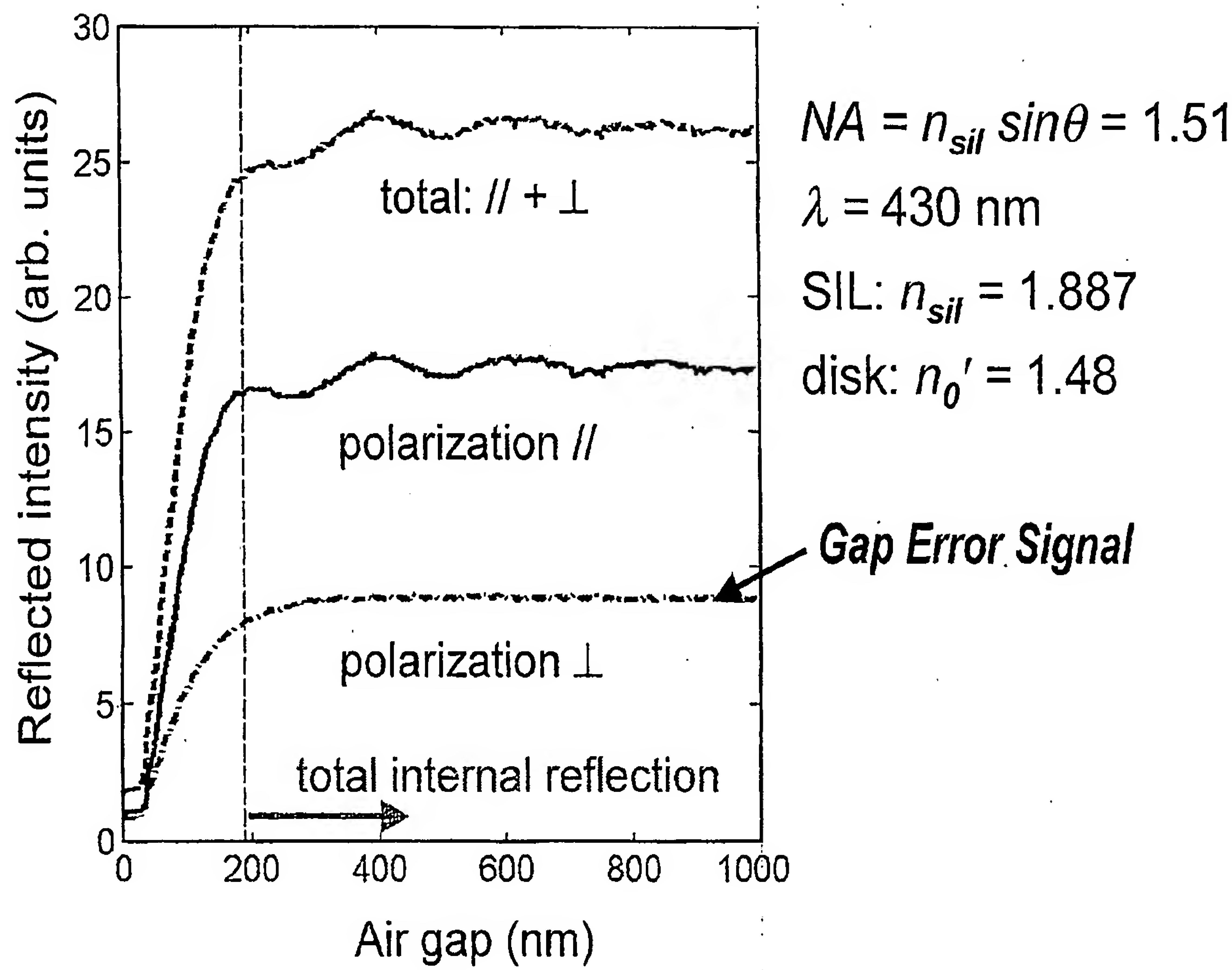
30
25
20
15
10
5
0
0
200
400
600
800
1000
Reflected intensity (arb. units)
Air gap (nm)
total: // + ⊥
polarization //
polarization ⊥
total internal reflection
NA = n_sil sinθ = 1.51
λ = 430 nm
SIL: n_sil = 1.887
disk: n_0′ = 1.48
Gap Error Signal

Fig. 4

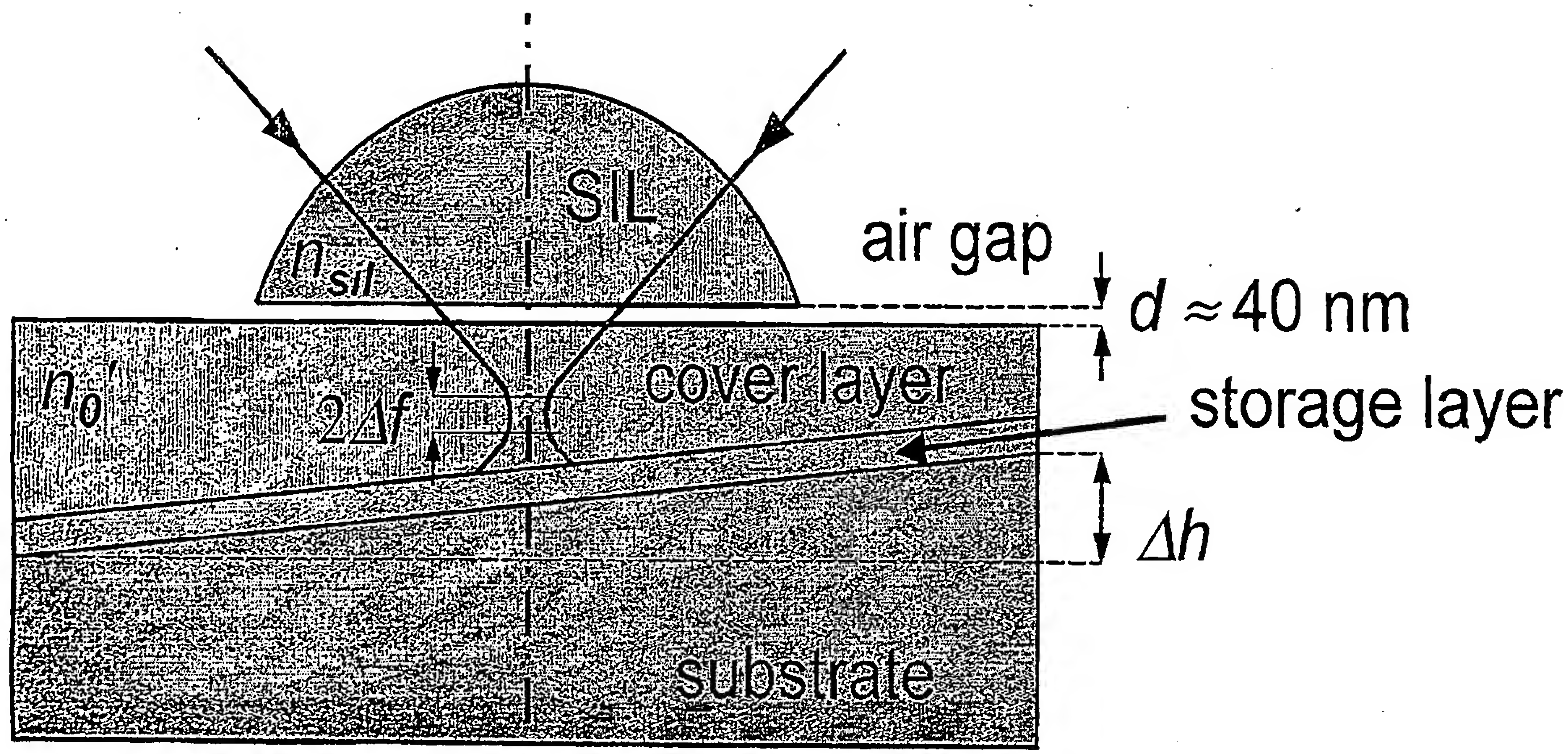
SIL
n_{sil}
air gap
$d \approx 40$ nm
n_0'
$2\Delta f$
cover layer
storage layer
Δh
substrate

Fig. 5

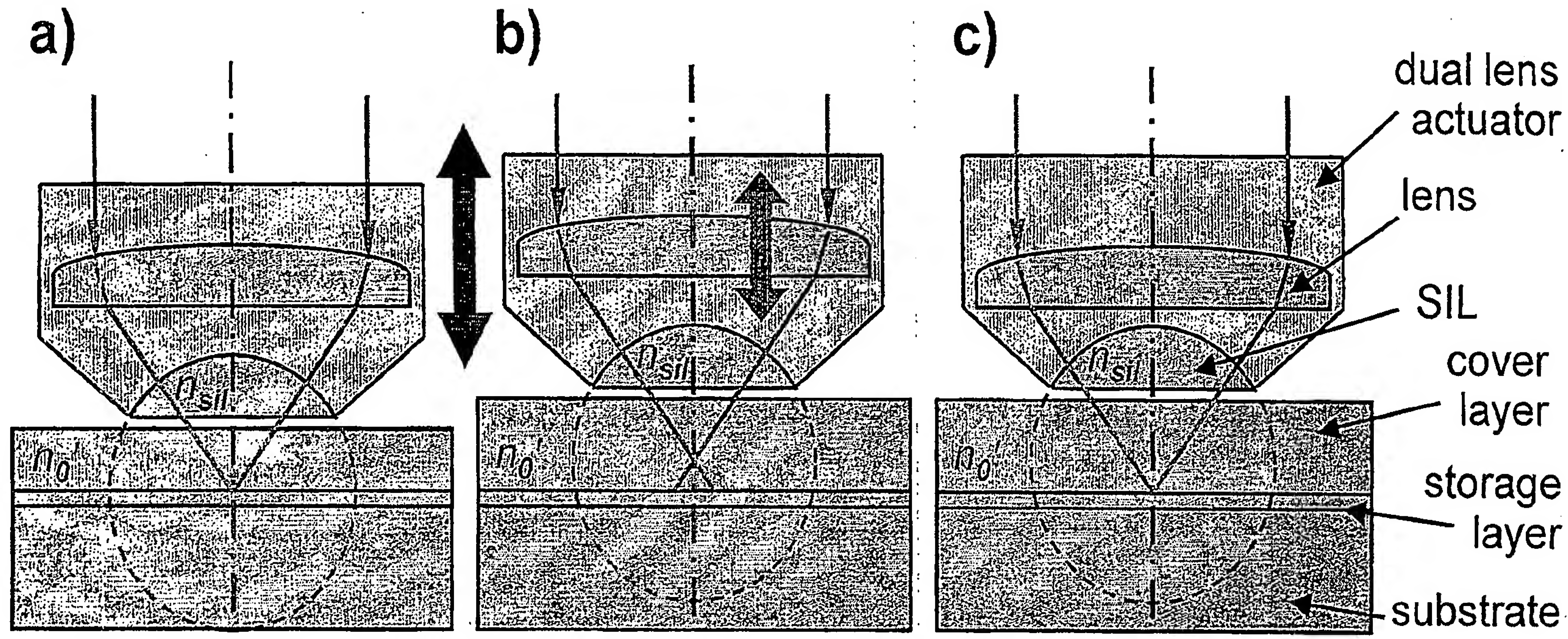
a)
b)
c)
dual lens actuator
lens
SIL
cover layer
storage layer
substrate
n_{sil}
n_0

Fig. 6

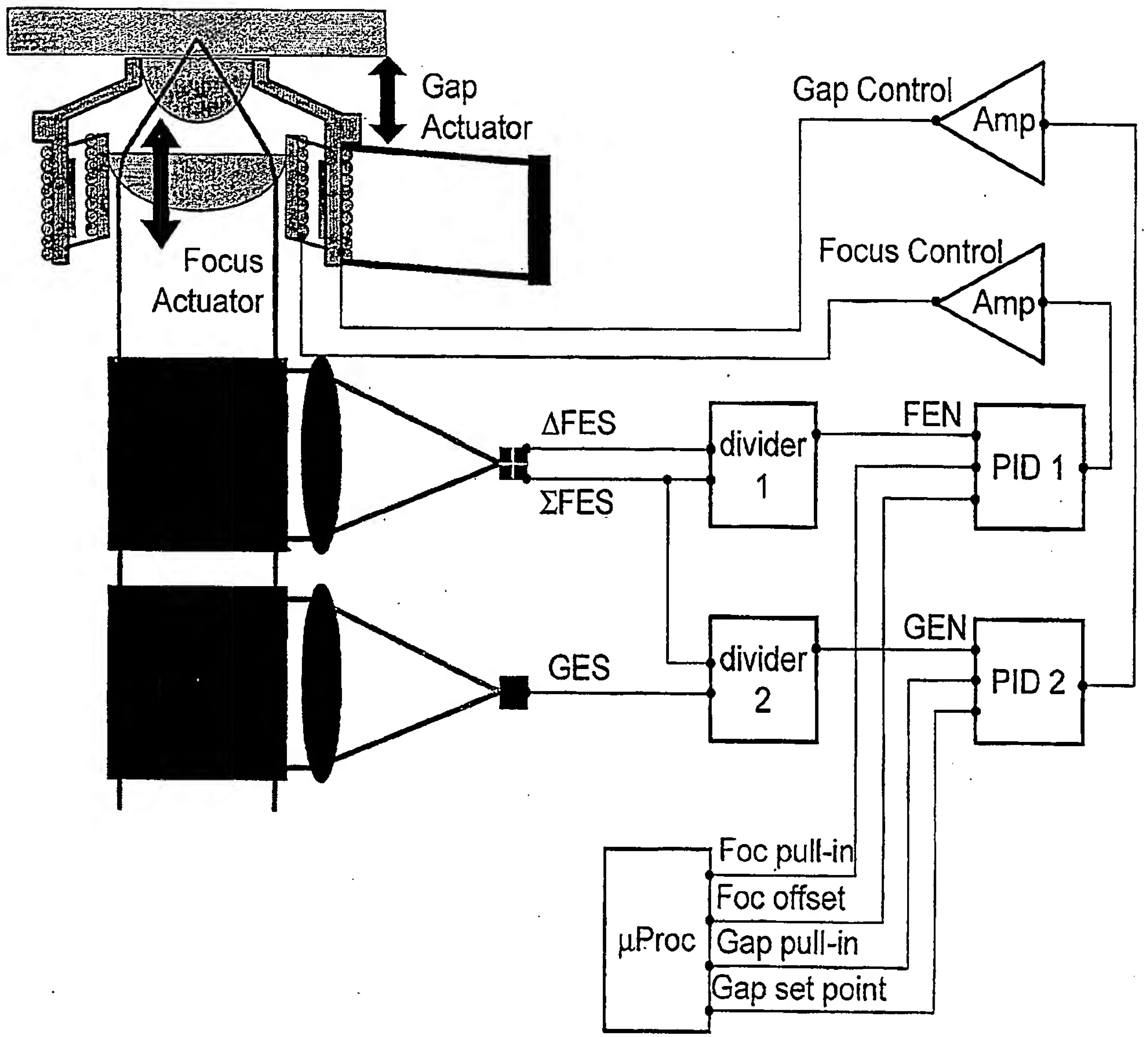
Gap
Actuator
Focus
Actuator
Gap Control
Amp
Focus Control
Amp
ΔFES
ΣFES
GES
divider
1
divider
2
FEN
GEN
PID 1
PID 2
μProc
Foc pull-in
Foc offset
Gap pull-in
Gap set point

Fig. 7

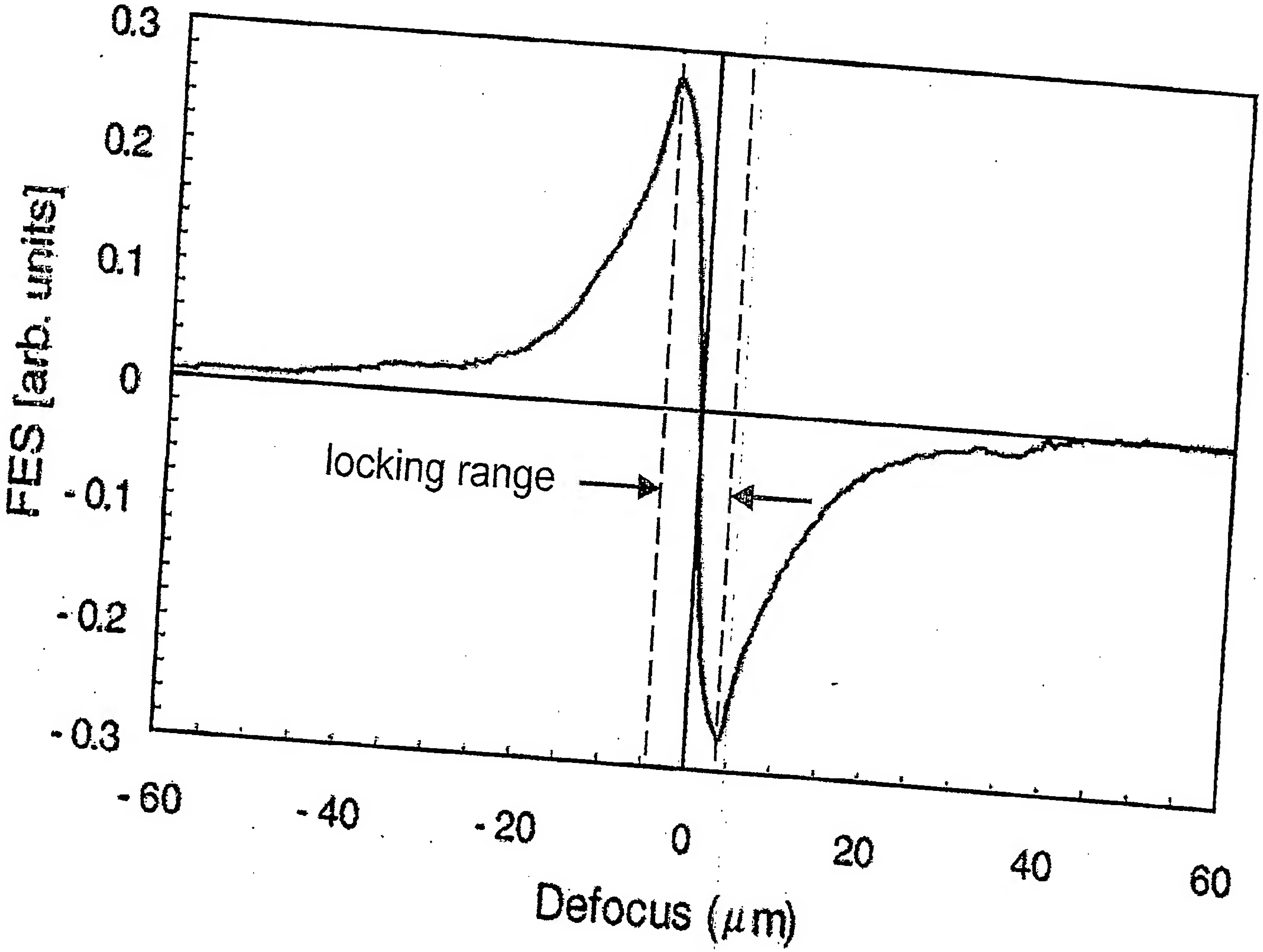
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
FES [arb. units]
locking range
-60
-40
-20
0
20
40
60
Defocus (μm)

Fig. 8

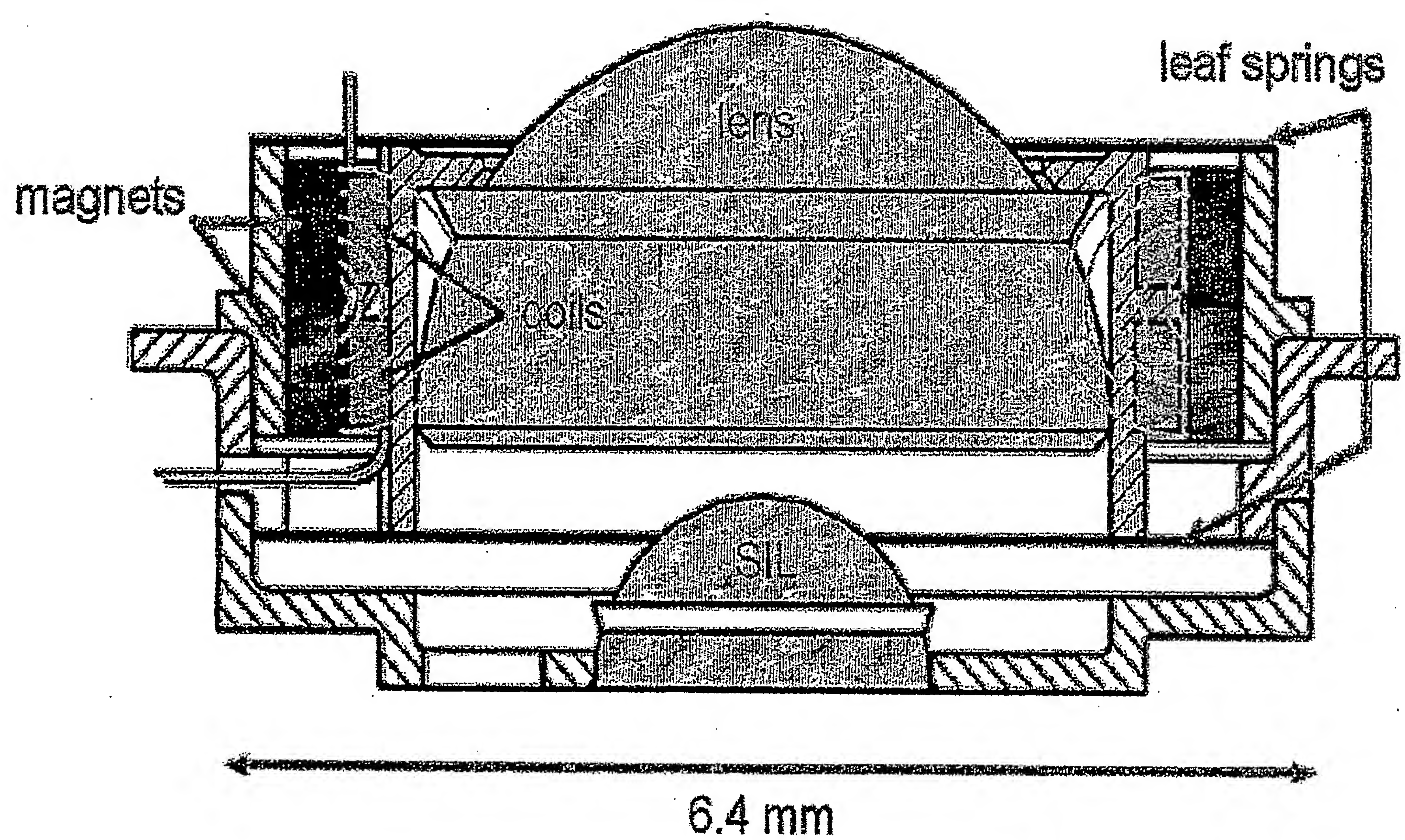

Fig. 9

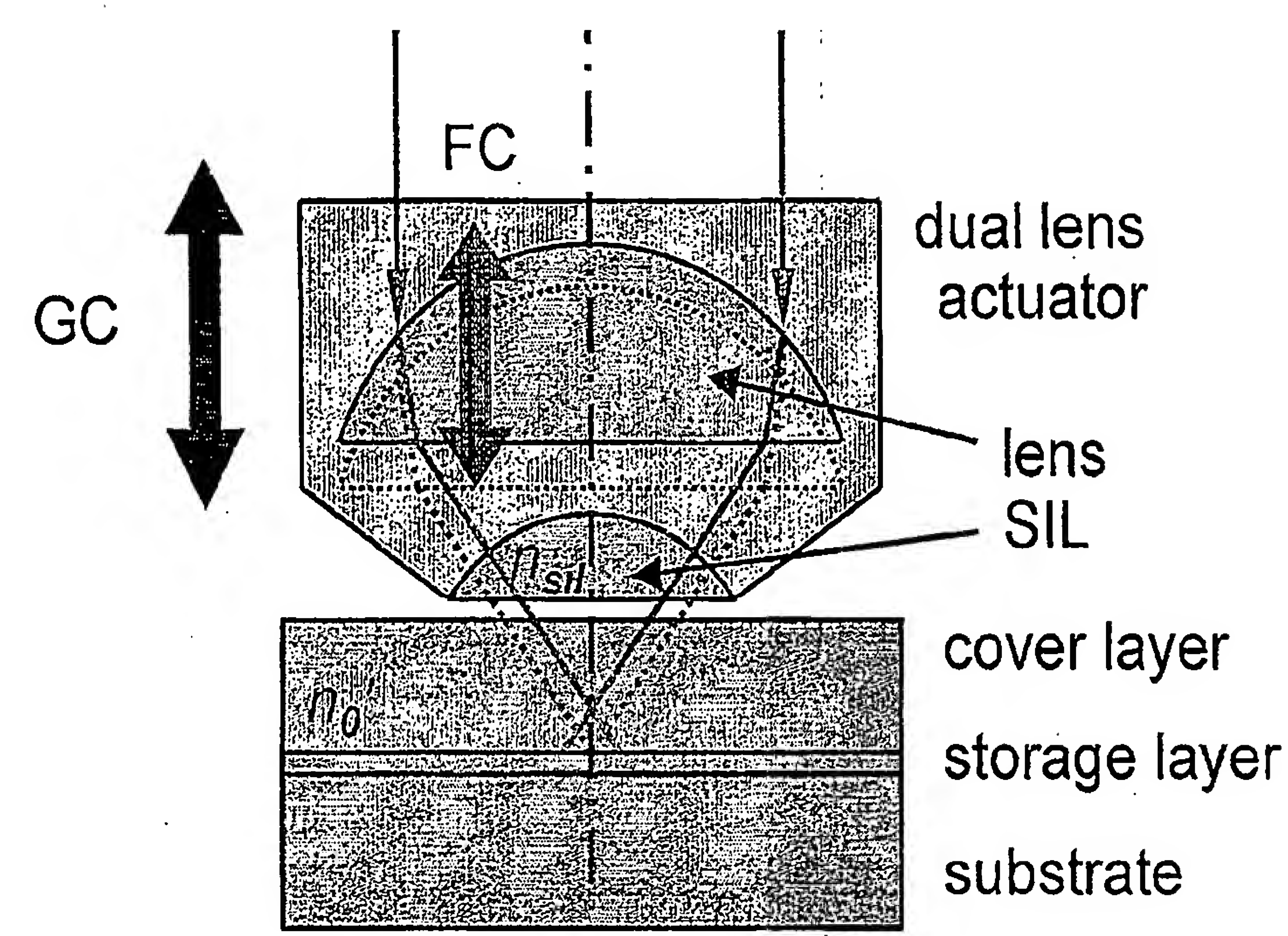
FC
GC
dual lens actuator
lens
SIL
n_{sil}
n_0
cover layer
storage layer
substrate

Fig. 10

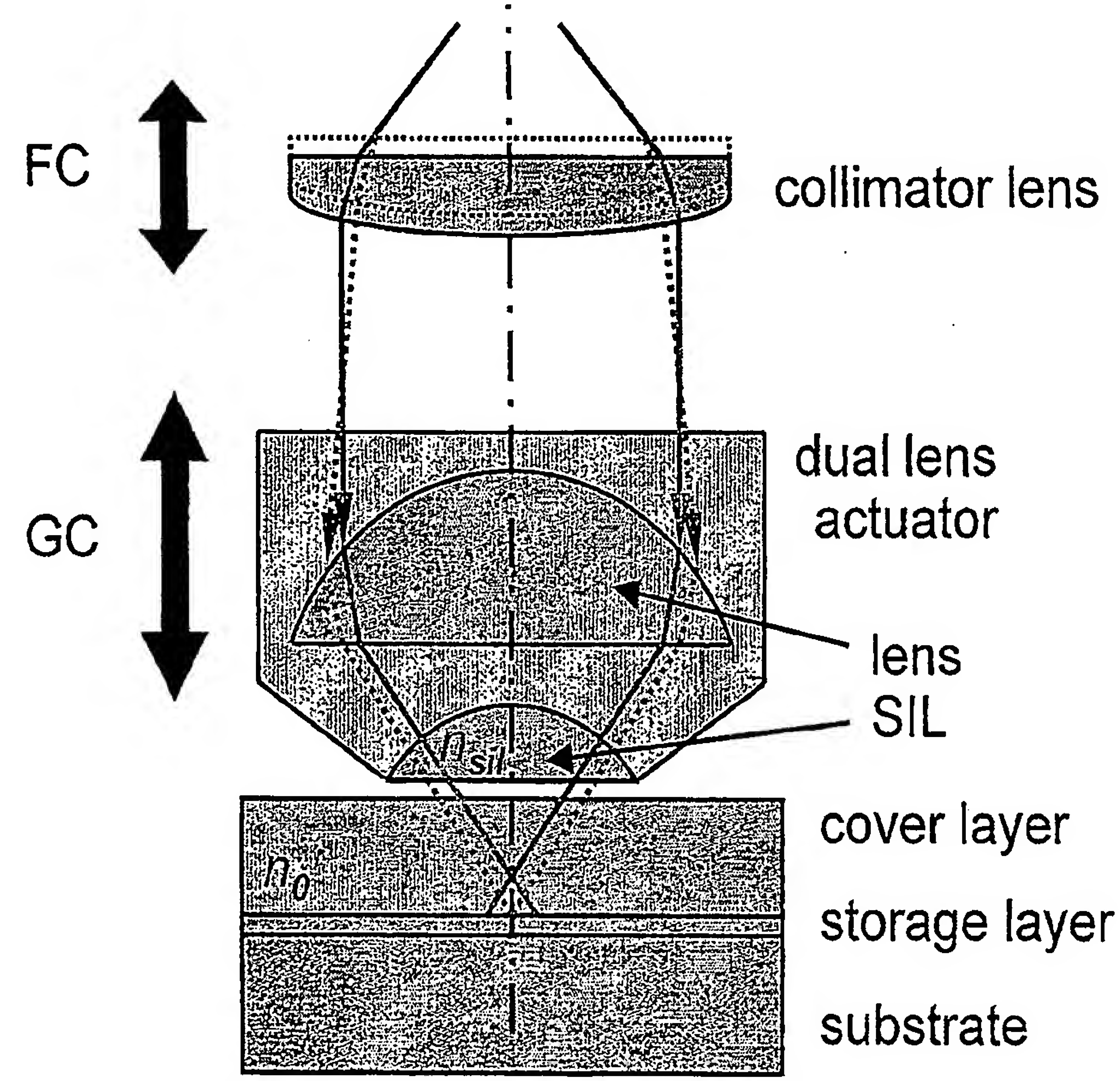
FC
GC
collimator lens
dual lens
actuator
lens
SIL
n_{sil}
cover layer
n_0
storage layer
substrate

Fig. 11

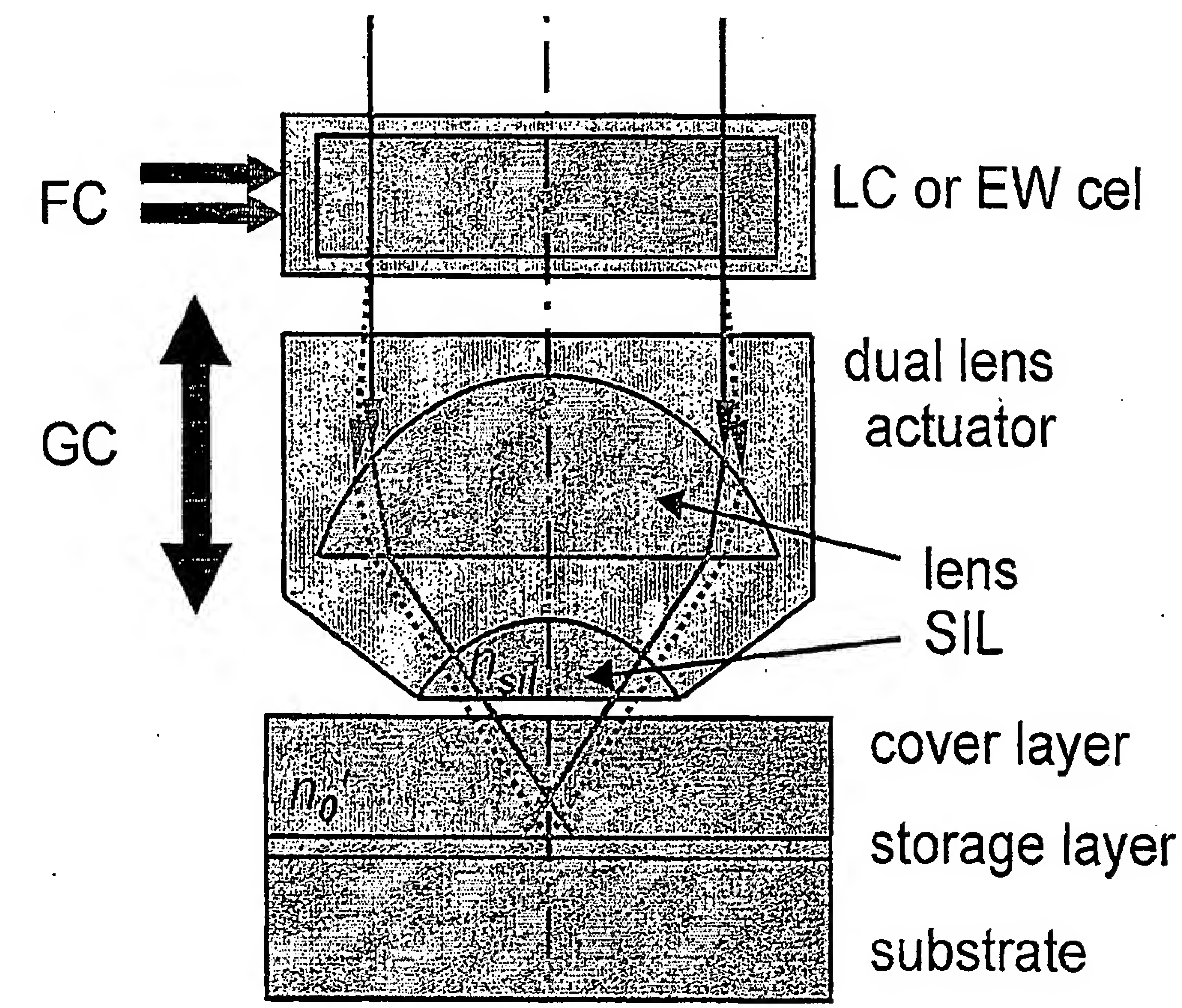
FC
GC
LC or EW cel
dual lens
actuator
lens
SIL
n_{sil}
n_0
cover layer
storage layer
substrate

Fig. 12

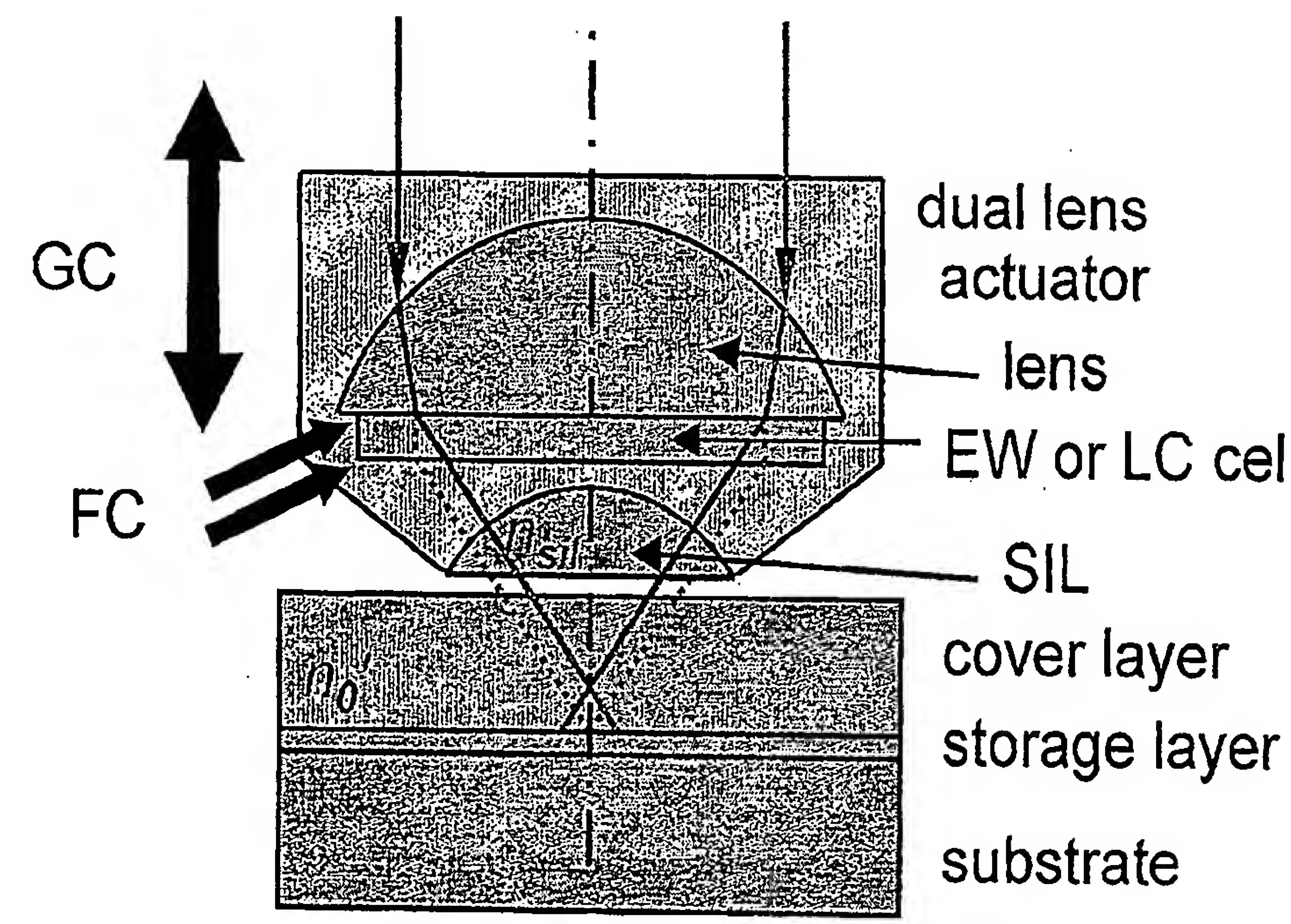
GC
FC
dual lens actuator
lens
EW or LC cel
SIL
n_{SIL}
n_0'
cover layer
storage layer
substrate

Fig. 13

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